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Galactic Cosmic Ray Isotope Spectroscopy: Status and Future Prospects

R. A. Mewaldt
California Institute of Technology
Pasadena, CA 91125

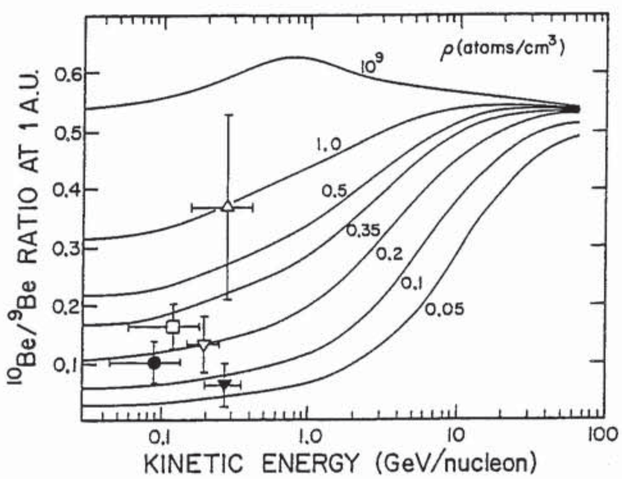
Abstract: A brief review of cosmic ray isotope spectroscopy is presented, focusing on cosmic ray clocks and the composition of cosmic ray source material. Some of the goals and prospects for future cosmic ray isotope spectrometers are discussed.

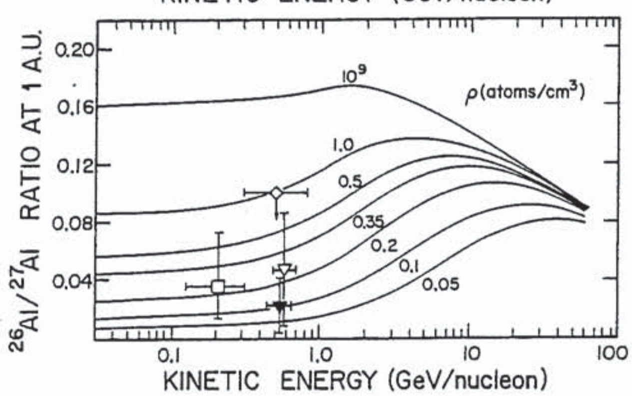
1. Introduction

The relative abundances of the isotopes of galactic cosmic rays represent a record of the nuclear history of a sample of matter from other regions of the galaxy, including its synthesis in stars, and its subsequent nuclear interactions with the interstellar gas. Recent progress in cosmic ray isotope spectroscopy has revolutionized our views of both cosmic ray origin and propagation. In this paper the present status of cosmic ray isotope measurements and prospects for future progress are briefly reviewed, including possibilities for improving on the yield and energy coverage of present experiments by more than two orders of magnitude. For more complete discussion and references on many of these topics, there are a number of other recent reviews[1,2,3,4,5].

2. Cosmic Ray Clocks and Secondary Nuclei

There are several long-lived radioactive isotopes produced as "secondaries" in cosmic ray interactions with the interstellar medium (ISM) that can be used to measure the average lifetime of cosmic ray propagation in the galaxy. Examples are ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, and ^{54}Mn. Figure 1 shows measurements of two of these cosmic ray clocks: ^{10}Be (half-life = 1.6 x 10^6 yr) and ^{26}Al (half-life = 9 x 10^5 yr), along





Figures 1 and 2: The ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios vs. energy per nucleon, with the Calculations by Guzik and Wefel[6], parameterized by the density of the propagation region. References to measurements (by Berkeley, Chicago, Goddard, Minnesota, and New Hampshire) can be found in 1); recent data is from references 7) and 8).

with calculations parameterized by the density of the propagation region. Note that both ^{10}Be and ^{26}Al suggest a density of ~ 0.2 atoms/cm^3, substantially less than the average density of matter in the galactic plane. For a mean free path of 6 g/cm^2 for escape from the galaxy the "lifetime" is $\sim 2 \times 10^7$ years, much younger than solar system matter. The similar lifetimes for ^{10}Be and ^{26}Al, suggest that their parents share a common history.

With improved precision, measurements of clocks with different half-lives can determine the *uniformity* of the matter density traversed, and thereby test whether some of the matter is in the source region. In addition, measurements of clocks over a broad energy interval can test whether continuous acceleration is occurring in the galaxy as a result of encounters with supernova shock waves. Finally, studies of Fe, Ni, and Co electron-capture isotopes can determine the time-delay between nucleosynthesis and cosmic ray acceleration.

There has been a great deal of recent interest in the secondary isotopes ^2H and ^3He, as a result of indications that cosmic ray H and possibly He may have had a different origin and history from that of heavier nuclei. In particular, a number of models [see, e.g., ref 9)] designed to explain the excess of antiprotons observed at GeV energies have suggested that at least some ^1H and ^4He nuclei have traversed considerably more matter than heavier nuclei, which would also produce an excess of ^2H and ^3He. Although recent studies[10,11,12)] find no evidence for an excess of ^3He beyond that expected from standard models, the ^2H situation is less clear, and most observations are at low energies (<300 MeV/nucleon), far below the threshold for antiproton production.

3. Source Abundances of Cosmic Ray Isotopes

Over the last decade it has been shown that the matter from which cosmic rays originate has a distinctly different isotopic composition from typical solar system matter. In particular, ^{22}Ne is at least a factor of three times more abundant in cosmic ray source material, while the abundances of the neutron-rich isotopes ^{25}Mg, ^{26}Mg, ^{29}Si, and ^{30}Si are all enhanced by a factor of ~ 1.5. This anomalous isotopic composition implies that the nucleosynthesis of cosmic ray and solar system matter has differed, a discovery that has stimulated a number of new theoretical suggestions as to how such differences might have occurred. To test these models will require extending observations to other elements to see if this pattern of differences continues. Unfortunately, progress has been slow because of the lack of launch opportunities for new instruments. Since reviews[1,2,3)] prepared a few years ago, the New Hampshire group has reported new observations[8)] that support earlier reports of a very low ^{14}N abundance [see, e.g., refs. 2,5)] and confirm the $^{25,26}Mg$ enhancements in cosmic ray source material, while their $^{29}Si/^{28}Si$ and $^{30}Si/^{28}Si$ ratios are consistent with solar system values (with sizable uncertainties). Table 1 and Figure 2 present an updated summary of the isotopic composition of the cosmic ray source, based on a weighted mean of those results with the best mass resolution [see also 5)].

Another area of recent progress is the measurement of cross sections required to obtain the source composition from the measured composition. For example, the source abundance of ^{13}C has had a large uncertainty due to the sizable secondary contribution of ^{13}C produced during propagation, and the assumed 35% uncertainity in the semi-empirical cross sections used[14)]. Preliminary cross section measurements reported recently allow an improvement in the ^{13}C source abundance[15)]. Although propagation uncertainities still dominate

Table 1

Comparison of Cosmic Ray Source and Solar System Isotopic Composition

Abundance Ratio	Cosmic Ray Source / Solar System
$^{13}C/^{12}C$	1.6 ± 0.9
$^{18}O/^{16}O$	$\leqslant 4$
$^{22}Ne/^{20}Ne$	3.5 ± 0.6 or 5.8 ± 1.0 a)
$^{25}Mg/^{24}Mg$	$1.6 \pm ^{0.4}_{0.3}$
$^{26}Mg/^{24}Mg$	1.6 ± 0.25
$^{29}Si/^{28}Si$	$1.5 \pm ^{0.4}_{0.35}$
$^{30}Si/^{28}Si$	$1.5 \pm ^{0.4}_{0.3}$
$^{34}S/^{32}S$	$\leqslant 4$
$^{54}Fe/^{56}Fe$	$\leqslant 1.7$
$^{58}Fe/^{56}Fe$	$\leqslant 10$

a) Depending on whether 0.073 or 0.122 is used for the solar system standard.

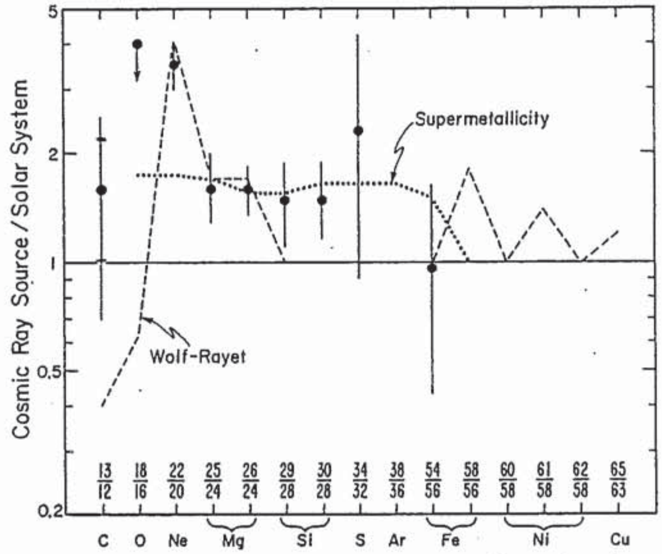


Figure 3: Comparison of measured and calculated cosmic ray source and solar system[13] compositions. The data points are based on a weighted mean of selected measurements, updated from 2). Dotted extensions to the ^{13}C error bar indicate the propagation uncertainty.

the revised $^{13}C/^{12}C$ ratio in Table 1 and Figure 3, and it is not yet possible to tell if there is an excess of ^{13}C, the uncertainity may be reduced further in the next year or two. Recent cross section measurements[16] have also supported the conclusion that cosmic ray source material is deficient in ^{14}N, and they have confirmed that the enhancements of ^{22}Ne, $^{25,26}Mg$, and $^{29,30}Si$ reported earlier could not be the result of secondary production during propagation.

4. Interpretation of the Cosmic Ray Source Composition

Of the models proposed to explain the observed excess of neutron-rich isotopes in cosmic rays, the most quantitative are the so-called "supermetallicity" model of Woosley and Weaver[17], and the Wolf-Rayet model proposed by Casse and Paul[18]. Woosley and Weaver pointed out that the production of neutron-rich isotopes in massive stars is proportional to the initial "metallicity" (the fraction of $Z>2$ elements) of the material from which the star formed, and proposed that the excess of neutron-rich isotopes might result if cosmic rays originate in regions of the galaxy that are metal-rich compared to the solar system. They predicted similar enhancements for a number of other neutron-rich nuclei including ^{18}O, ^{34}S, ^{38}A, and ^{54}Fe, as shown in Figure 3. Note that this model is consistent with the approximately equal enhancements observed for the Mg and Si isotopes, but it would apparently require an additional source of ^{22}Ne to explain the large $^{22}Ne/^{20}Ne$ ratio in cosmic rays.

In the Wolf-Rayet (WR) model it is assumed that a fraction of heavy cosmic rays originate from the material that has been expelled by Wolf-Rayet stars. These massive stars are undergoing significant mass loss by means of high-velocity stellar winds. As a result they have been stripped of their hydrogen envelopes, and helium-burning products including ^{12}C, ^{16}O, and ^{22}Ne have been exposed and are being expelled from their surface. Casse and Paul suggested that if a fraction of cosmic rays were to originate from WR material, this might explain both the excess of ^{22}Ne and also the fact that $C/O \simeq 1$ in cosmic rays, compared to $C/O \simeq 0.5$ in the solar system.

Figure 3 includes predictions due to Prantzos et al.[19], that when normalized to ^{22}Ne, match the observed ^{25}Mg and ^{26}Mg enhancements, but do not produce an excess of either ^{29}Si and ^{30}Si; one of several differences from the supermetallicity model. The WR model also predicts enhancements of s-process nuclei such as ^{58}Fe, and it leads to a depressed $^{13}C/^{12}C$ ratio as a result of the large amount of pure ^{12}C expected from WR stars. Note in Figure 3 that the ^{13}C point is in mild disagreement with this prediction; a possible resolution of this difference is discussed below. Other possible problems for this model include the low ^{14}N abundance in cosmic rays, and the fact that these relatively rare stars must apparently produce $\sim$25% of heavy ($Z \geq 6$) nuclei in cosmic rays[5].

5. Composition and Evolution of Galactic Material

Cosmic ray composition information complements that from other spectroscopic studies, including millimeter-wave observations of molecular clouds[20,21]. Figure 3 compares the cosmic ray source composition with average isotopic ratios in the galactic center and galactic disk regions. Note that the millimeter-wave observations have produced clear evidence that the composition in the galactic center region differs from that of solar system material, including variations much greater than typically found in solar system material. There is also evidence for such differences in the galactic plane.

Recently Hawkins and Jura[23] reported optical measurements of the $^{13}C/^{12}C$ ratio in four different directions that yield a $^{13}C/^{12}C$ ratio in the local neighborhood a factor of 2.1 ± 0.2 greater than the solar system value. These new observations, which are consistent with several galactic chemical evolution models, provide proof that the composition of the local neighborhood has evolved since the formation of the Sun. It is interesting that if WR material is mixed with material characteristic of the present-day local ISM, as would seem appropriate in this model, the difference between the measured and predicted $^{13}C/^{12}C$ ratios (Figure 3) would disappear. Although the rate of evolution of the local $^{13}C/^{12}C$ ratio does not necessarily imply similar changes in heavier neutron-rich isotopes because of differences in their origin[24], it does show that evolutionary effects are important

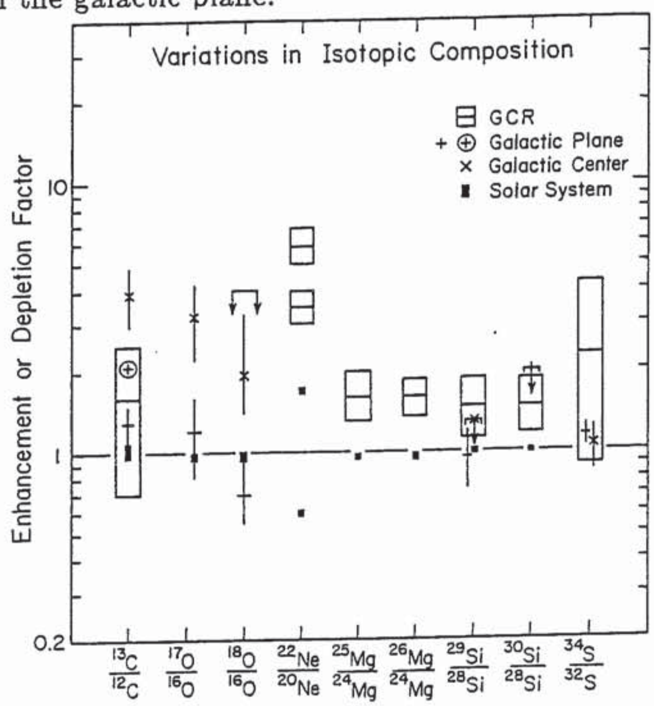


Figure 4: Comparison of variations in isotopic composition detected in galactic cosmic rays with those detected in the galactic plane and center regions using other techniques,[20,21] and with those found in solar system material.[22] The circled cross is the recent observation by Hawkins and Jura.[23]

locally on relatively recent time scales, and it underscores the need for both theoretical modeling and further measurement of galactic isotope ratios via cosmic ray and other observations.

6. Future Prospects

Our knowledge of the isotopic composition of cosmic ray source material is still very limited. Only the Ne, Mg, and Si isotopes have had their source abundance determined to an accuracy of ~30% or better, and in each case differences from the solar system composition have been found. If such observations are to be extended to other elements such as Fe and Ni, it will be necessary to expose larger instruments in space. The techniques for resolving isotopes have now been proven, they need only be applied on a larger scale. In the next few years two instruments built by the University of Chicago for the Ulysses and CRRES missions (a similar Goddard experiment is planned for ISTP/WIND) should collect a factor of ~10 more data than the ISEE-3 instruments, determining composition of the more abundant isotopes from ~100 to ~300 MeV/nucleon. At somewhat higher energies, further results can be expected from balloon-borne experiments. Beyond this, the Cosmic Ray Program Working Group[25] in its "Particle Astrophysics Program for 1985-1995" identified the need for two major new projects that would improve on existing observations by more than two orders of magnitude: a superconducting magnet facility for particle astrophysics on the Space Station, and a cosmic ray composition Explorer. To meet this need two possible missions have been proposed.

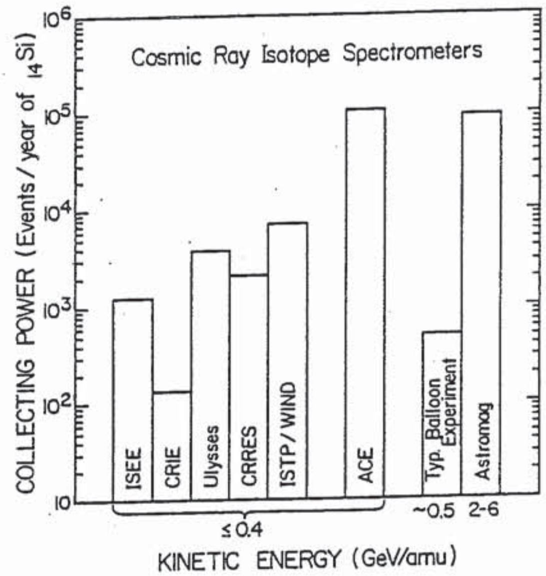


Figure 5: A comparison of the collecting power of previous cosmic ray isotope spectrometers (ISEE, CRIE) with that of planned or proposed instruments.

The Advanced Composition Explorer (ACE) would measure the isotopic and elemental composition of several samples of matter with unprecedented resolution and collecting power, including galactic cosmic rays (30-400 MeV/nucleon), the "anomalous" cosmic ray component (thought to represent a sample of the neutral ISM), energetic particles accelerated in solar flares, and the solar wind. *Astromag,* the superconducting magnet facility being planned for the Space Station[26], would extend cosmic ray isotope measurements to energies from ~2 to as high as ~50 GeV/nucleon, allowing clocks such as ^{10}Be to be read over a wide range of time-dilation factors, and extending measurements of the source composition up to high energies. *Astromag* would also measure the spectra of antiprotons, electrons, positrons, and heavy nuclei, and make a sensitive search for antinuclei. As indicated in Figure 4, the collecting power of both ACE and *Astromag* would be more than an order of magnitude greater than that of any previous or planned experiment, sufficient to obtain definitive measurements of even rare species.

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